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STUDENT DIFFICULTIES WITH CHEMICAL CONCEPTS: VOLUMETRIC ANALYSIS

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STUDENT DIFFICULTIES WITH CHEMICAL CONCEPTS:

VOLUMETRIC ANALYSIS*

by

Jophus Anamuah-Mensah

August 1981

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Introduction

For some time now, science educators have been called upon to increase the amount of research on the difficulties that science students have on specific science concepts if science education in the schools is to be improved (Shulman and Tamir, 1973; Driver and Easely, 1978; Levine and Linn, 1977).

To this end, studies have been done which have attempted to look at students' difficulties with specific science concepts. In chemistry, a number of studies have been done with concepts such as the mole and stoichiometry. However, one could literally classify these studies into two groups according to the dominant psychological theory being applied.

In one group of studies exemplified by Herron (1975); Ingle and Shayer (1971), Chiapetta (1974), Piaget's proportional reasoning schema or formal operations has been used as the dominant explanatory construct to account for students' difficulties. In other words, these studies have sought to explain subjects' difficulties on chemical problems only in terms of the operational structures demanded by the problems. In addition, these studies have not distinguished between the ability to reason using inverse proportion from the ability to reason using direct proportion even though there's some evidence to suggest a temporal order in acquisition.

In the second group of studies exemplified by studies by Gower, Daniels and Lloyd (1977a, 1977b), Duncan

and Johnstone, (1973), Novick and Menis, 1977, the prerequisite concepts or content subsumed by the major concept of interest has been used to explain students difficulties on specific chemical concepts. These studies have generally employed Gagné's skill integration approach in their analyses of students' difficulties. The study by Rowell and Dawson (1980) examined the steps used by the subjects to solve stoichiometric problems in order to identify their difficulties.

Only a few studies sought to use both the operational structures and prerequisite content to explain the students difficulties. But even these studies failed to examine the connection among the explanatory variables.

Thus in general studies on the difficulties of subjects on certain chemical concepts have failed to examine these variables together in the same study. In addition, the likely 'causal' connections among these contributory variables have not been systematically studied.

The importance of examining these contributory variables in the same study is noted in a suggestion by Kuhn (1979) that some of the problems science educators encounter in applying psychological theories to their specific areas reflect the weaknesses inherent in the theories themselves. By recognizing these weaknesses one could combine a number of theories so that some of the weaknesses in one theory could be taken care of by the strengths of other theories. Sticht (1971) has also made a similar point.

In line with this, the present study which examines a persistent problem in high school chemistry, namely, the difficulties that students experience with volumetric analysis calculations, draws upon two theoretical frameworks - the proportional reasoning schema in Piaget's theory of intellectual development and Gagné's cumulative learning theory to identify the influence of structure and content in understanding volumetric analysis calculations.

Apart from the development and statistical validation of the above relationships, the study also examined the specific difficulties (both conceptual and manual) that students have on volumetric analysis. This was done so as to gain a much detailed and broader understanding of students' difficulties with volumetric analysis.

The choice of volumetric analysis was suggested by the concerns expressed by some chemical educators (Herron, 1975; Wheeler and Kass, 1977) on the complexity of the concept and the awareness of both chemistry teachers and researchers about the apprehensions students have when doing volumetric analysis problems (Johnstone, Morrison and Sharp, 1976; Duncan and Johnstone, 1973).

It is hoped that if the difficulties which students encounter with volumetric analysis problems could be identified, then it may be possible to design teaching strategies which would help to alleviate these difficulties. In addition, the isolation of the sources of difficulty may help in understanding how these sources independently and collectively affect

the processing abilities of students, specifically, how they come to understand volumetric analysis problems.

Research Questions

The research questions posed in the study were grouped into two according to whether they fell under the first part of the study (i.e. model testing) or the secondary section of the study (i.e. specific difficulties).

As suggested in the literature, students who use certain algorithms in their solutions to chemical problems may do so either with or without understanding of the algorithms (Chiappetta, 1974; Smith, 1978). Thus, an attempt was made in this study to identify these two groups of students through the form of their responses to the Volumetric Analysis Test. Students who used algorithms indiscriminately, (e.g. they used a 1:1 mole ratio when it was not applicable) formed one group while those who used algorithms discriminately (e.g. they used a 1:1 mole ratio with an understanding of when to apply it) comprised the second group. It was hypothesized that since these groups of subjects might respond differently to the tests used in the study, the proposed model might fit the data for one group more closely then for the other. Hence, the first question addressed was:

Question 1:

Does the integrated model account for the observed data for the two groups of subjects to the same extent?

Apart from this, an additional research question was posed for testing the model against the total sample. However, as will be shown in the results section, marked differences were found between the two groups. As such it was decided against performing the test on the total sample since pooling the scores for the two groups may lead to confounded results.

The research questions addressed in the secondary part of the study were:

Question 2:

What conceptual errors are made by students on the Volumetric Analysis Test?

Question 3:

What practical laboratory skills do subjects display in a titration experiment?

Question 4:

What difficulties do subjects have with concepts involved in an actual titration experiment?

Question 5:

What are the different approaches used by the subjects in solving a volumetric analysis problem?

Question 6:

Is the number of laboratory titrations performed related to students' performance on the Volumetric Analysis Test?

Methodology

The methodology employed in the first part of the study falls in the domain of what Wold (1956) and Lohnes (1979)

call Explanatory Observational Studies. This approach involves the explanation of observable phenomena through the postulation of a theoretical causal model in which the causal directions among the variables in the model are specified. Observational measures on the variables are then obtained and used to establish the plausibility of the causal model through statistical analysis. In the second part of the study qualitative procedures (e.g. categorizing response patterns and conceptual errors) were employed.

A. The Proposed Integrated Model of Performance

In developing the causal model involving the four variables - direct proportion, inverse proportion, subsumed prerequisite concepts and volumetric analysis calculations, studies reported in the science education literature which related primarily to students' understanding of chemical concepts were employed.

Studies conducted by Piaget and his associates indicate that problems of direct proportionality as in the experiments on the notion of similar triangles (Piaget, 1957) tend to be solved during early adolescence (i.e. around ages 11 and 12) while problems of inverse proportionality such as the Equilibrium in the Balance Task (Inhelder and Piaget, 1958) are solved at a later age (Lovell, 1971). That is, there is a temporal order of development between direct proportion and inverse proportion. A stronger evidence for this was given by Rogers (1977) in an experimental study aimed at

testing for a developmental sequence of acquisition of proportional reasoning in 16 year old high school physics students. The Paper Clips Task (Wollman and Karplus, 1974) a first-order direct proportionality task, the Equilibrium in the Balance Task (a first-order inverse proportionality task) and two other tasks measuring second-order direct and second-order indirect proportionality were used in the study. Using an ordering-theoretic approach, Rogers found that a prerequisite sequence exist between the first order direct proportionality and the first order inverse proportionality. A study by Lunzer and Pumfrey (1966) gives further support to the above findings that acquisition of direct proportionality precedes that of inverse proportionality.

The connection between direct proportionality and the subsumed prerequisite concepts (or content) is indicated by the work of Ingle and Shayer (1971) and others (Herron, 1975; Wheeler and Kass, 1977; Chiappetta, 1979). Both Ingle and Shayer (1971) and Herron (1975) provided a theoretical analyses of the mole concept, stoichiometry and other chemical concepts. Their analyses, based on Piaget's theory, indicated that the mole, stoichiometry, gram/mole conversions and interpretation of equations require direct proportionality for understanding. Chiappetta (1979) has also indicated that stoichiometric calculation problems require (direct) proportional reasoning before an adequate understanding can be achieved. The study conducted by Wheeler and Kass (1977), showed a significant relationship between

proportional reasoning and achievement in a criterion test testing the mole, gravimetric stoichiometry and chemical reactions which require direct proportion (Ingle and Shayer, 1971). The proportional reasoning in the study was measured using both direct and inverse proportionality tasks. But as the final concepts tested involved only direct proportion one could conclude that direct proportionality was necessary for achievement in the final test.

By logical extension of the preceding discussion, a relationship between direct proportionality and volumetric analysis calculations can be established. The application of Piaget's theory suggests that direct and inverse proportionality constitute the formal structures underlying volumetric analysis calculations (Herron, 1975; Wheeler and Kass, 1977). The assumptions involved in the theory suggests that the solution to such a problem (i.e. volumetric analysis calculation) will require the prior presence of direct and inverse proportional reasoning. Indirect evidence in favour of the connection between inverse proportionality and volumetric analysis calculations is provided in the study by Chiappetta (1974) that looked at the inverse proportional reasoning of subjects (measured using the Equilibrium in the Balance Task) and performance on a chemical solubility test. A moderate correlation (0.60) was found which may indicate the dependence of achievement in chemical concepts on inverse proportionality.

One of the subsumed prerequisite concepts in the present study is the calculations involved in the dilution of

concentrated solutions. Analysis of such problems using Piaget's theory suggests that inverse proportionality underlies such problems (Herron, 1975). The implication is that solutions to these problems depend on the understanding of inverse proportionality.

No empirical study was found in the literature to show the influence of subsumed prerequisite concepts on volumetric analysis calculations per se. However, a number of studies have reported on the influence of subsumed concepts on other chemical concepts. The study by Griffiths (1979) on the effect of concepts subsumed by the mole concept showed that the subsumed content were required for optimum performance on the problems related to the mole. The subsumed prerequisite concepts in the study were generated by using Gagné's hierarchical theory. A similar study conducted by Gower, Daniels and Lloyd (1977b) gave identical results. Okey and Gagné (1970) conducted a study in which the criterion variable was solubility product calculations. Using the hierarchical theory postulated by Gagné, they found that the difficulties encountered by the high school chemistry subjects used in the study were due to lack of the subsumed prerequisite concepts hypothesized in the study. The results of other studies (Duncan and Johnstone, 1971; Novick and Menis, 1976; Kass, 1977) indicate that success in a chemical task depends on the prior mastery of prerequisite concepts. From these studies, it can be hypothesized that knowledge of subsumed prerequisite concepts is necessary although not sufficient for successful per-

formance on volumetric analysis calculations. Also the basic assumption of the Gagnéan theory that the learning of a higher order concept (e.g. volumetric analysis) depends on the learning of the lower order concepts subsumed by it, lends support to this hypothesis.

A diagrammatic representation of the integrated model as postulated above is given in Figure 1. This model will be referred to as the proposed integrated model. The omission of the linkage between direct proportional reasoning and performance on volumetric analysis calculations in the integrated model is essentially a theoretical assertion; since it is subsumed by all the other variables in the integrated model, these variables should mediate the influence of direct proportional reasoning on volumetric analysis calculations. As shown in this recursive model, direct proportionality is an exogeneous variable (i.e. it is not influenced by other variables in the model) while inverse proportionality, subsumed concepts and volumetric analysis calculations are endogeneous variables. Since it is never possible to account for the total variance of a variable, residual variables R_4, R_3 and R_2 are introduced into the integrated model to indicate the effect of variables not included in the integrated model such as prior experience of subjects.

The figure uses a standard convention in the methodological literature of representing observed or measured variables by squares. Also by convention since a recursive model is proposed, paths in the form of unidirectional arrows

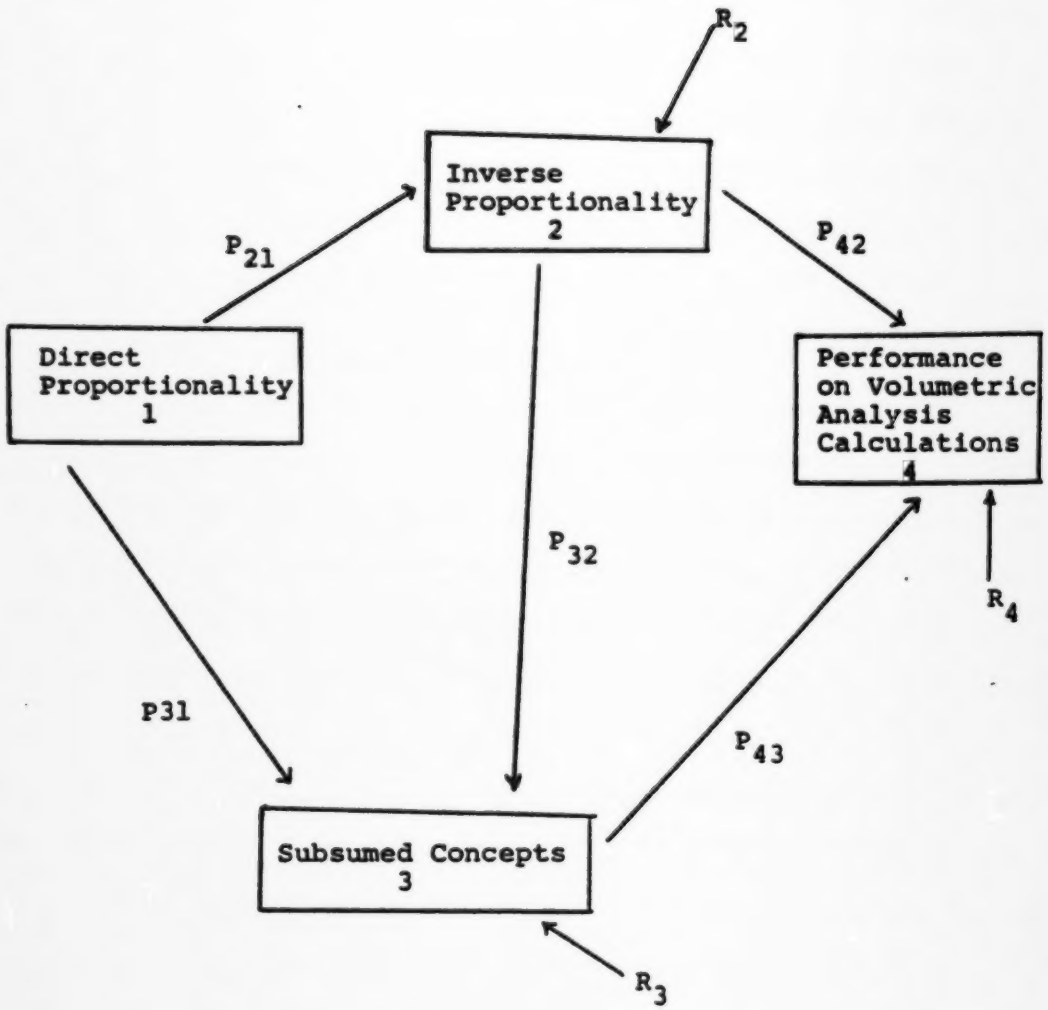


Figure 1: Proposed Integrated Model of Performance on Volumetric Analysis Calculations

are drawn to indicate the direction of the causal influence with the causal flow originating in the variables taken as "causes" or explanatory and yielding the variables taken as effects (Kerlinger and Pedhazur, 1973, P.308). The use of the word "cause" in path analysis is only colloquial; it "is meant to provide no philosophical meaning beyond a shorthand designation for a hypothesized unobserved process" (Bentler, 1980). Thus other words like explanatory or process could be used for the same end.

B. Population

The present study was an analytical study primarily designed to investigate the difficulties that senior secondary school students face when performing volumetric analysis calculations. Since volumetric analysis was only formally taught in the Grade 12 chemistry course of study in British Columbia, it was decided that students enrolled in the Grade 12 chemistry course in British Columbia would constitute the general population. However, the only area of British Columbia that was practical and available to carry out the study was the Lower Mainland. Thus for the purpose of this study, the students enrolled in Grade 12 chemistry courses in the Lower Mainland of British Columbia constituted the target population. Since Chemistry 12 is an optional course, normally only selected by more academically-oriented students, these subjects constituted a self selected group.

C. Sample

In May 1979, letters describing the objectives of the study and requesting permission to use selected schools in their districts were sent to four School Boards in the Lower Mainland. Two School Boards showed immediate interest in the study. Schools within the jurisdiction of these School Boards were contacted by School Board representatives. Of the 21 schools contacted, 10 volunteered to participate in the study. The locations of the schools were such that a wide geographical representation was obtained in the sample. Furthermore, the catchment areas of these schools represented a wide diversity of socio-economic levels as assessed by the School Board officials. The students in the intact classes in these schools constituted the sample for the study. There were initially 17 classes with a total student enrollment of 402 who wrote the first two instruments (CPT and SCT). However, due to logistical reasons (a delay in teaching the required unit on volumetric analysis) only eight schools with a total of 14 classes participated fully in the study, leaving a total number of subjects of 328 (203 boys and 125 girls).

D. Instruments and Procedures

Data on direct proportional reasoning (DP) and inverse proportional reasoning (IP) were collected through a group demonstration instrument, the Classroom Proportionality Test (CPT) using plastic cylinders and the Equilibrium in the Balance Task. Examples of items used in this test are provided

in Appendix A. This test was modified from the classroom test of formal operations (Lawson, 1978). The 7-item direct proportionality subtest was used to assess direct proportional reasoning in situations requiring 1:2, 1:3, 2:3 and 2:5 ratios. The 7-item inverse proportionality subtest was used to investigate inverse proportional reasoning in the following ratio situations: 1:2, 2:3, 1:3, 3:4, 3:5, 1:4, 1:5. The maximum score on each of the subtests is 21 points. The CPT was administered to the students in test booklets containing the questions and five possible answers. Spaces were provided where the students could record their reasoning. Hoyt estimate of reliability for the direct proportional reasoning and the inverse proportional reasoning subtests were 0.80 and 0.93 respectively.

Knowledge of prerequisite concepts (i.e. content) subsumed by volumetric analysis calculations was assessed through the use of a 28-item multiple choice test, the Sub-Concepts (SCT). This test consists of 7 subtests corresponding to the 7 prerequisite concepts derived from a Gagnéan type of analysis to be necessary for understanding problems in volumetric analysis (Gower, Daniels and Lloyd, 1977a). The prerequisite concepts are: mole, gram/mole conversion, writing equations, interpreting equations, stoichiometric calculations, computing concentration from mass of substances, and dilution calculations. Some of the items in this test were obtained from sources including tests used by Wheeler and Kass (1977) and Duncan and Johnstone (1971). Examples of some of the items

in this test can be found in Appendix A. The maximum score on this test is 28 points. The reliability (Cronbach's alpha) of this test was 0.78. Chemistry teachers participating in the study agreed to administer this test to their students as a review test before teaching the unit on volumetric analysis.

The students' performance on volumetric analysis problem was measured by using the 15-item Volumetric Analysis Test (VAT) (Appendix A). This test required the students to calculate the volume, concentration or mass of one of the reactants involved in a titration given the necessary data for the other reactant(s). The subjects were asked to respond to the items in the test by showing their answers as well as the steps used in their calculations. Achievement in this test was assessed by the number of correct answers obtained irrespective of the procedures (or steps) used. The maximum possible score on this test is 15.

The steps used by the subjects were examined for any conceptual errors made by the subjects. The steps were also used to identify subjects who use algorithms (i.e. mole ratios) with or without understanding of the stoichiometry involved. Using algorithms with understanding of the stoichiometry is defined as employing the correct stoichiometric ratios in computations, specifically using 1:1 and 1:2 mole ratios in test items requiring them. Using algorithms without understanding of the stoichiometry is defined as employing 1:1 mole ratios in more than two situations requiring other mole ratios.

A reliability (Hoyt estimate) of 0.88 was obtained from the administration of this test.

The Volumetric Analysis Test was administered to the students by the investigator in test booklets containing the questions and spaces where students record their answers and their computation procedures.

All the 3 tests took 50 minutes of administration time. Also, all the tests were pretested in a pilot study. The sequence of events in the administration of the three written tests is given below:

Test Administration and Inter-test Breaks

Tests administered prior to the teaching of volumetric analysis unit	Interval during which volumetric analysis (VA) was taught	Interval after teaching VA	Test administered	Interval before Interview	Interview period
CPT: DP Subtest 3 weeks SCT IP Subtest Interval	2 months-5 months	About 1 week	VAT	About 7 days	3 days-1 week

Because of logistical reasons in two of the schools participating in the study, only 8 schools could participate fully in the study.

All the instruments were administered to the subjects following the Grade 12 chemistry course in the 8 schools. The number of subjects in the 8 schools was 328.

After administering the Volumetric Analysis Test, six subjects were selected from each of the 8 schools involved in the study for an individual interview on a titration task. The subjects were selected on the basis of their scores on the VAT. In each school 2 subjects were randomly selected from those who scored from 0-5, from 6-10 and from 11-15. Briefly, in this interview subjects were asked to find the molarity of HCl in a titration situation in which the molarity of NaOH is known. The subjects were supplied with all the necessary materials needed for performing the titration including 3 indicators from which they had to choose one. During the interview, a checklist, Laboratory Skills in Titration, also pretested in a pilot study, was used to identify the laboratory skills of the subjects.

E. Analysis

Statistical hypotheses were stated for the questions related to (a) the model testing and (b) the correlation between number of laboratory titrations and performance on volumetric analysis calculations.

All the statistical hypotheses were tested at the 5 percent level of significance. Path analysis technique was used to evaluate the influences among the variables in the model. Recent developments employing chi-square goodness of fit test were used in the evaluation. Effect decomposition of the total associations between variables was done to identify the different effects of the variables in the integrated model. This was done by applying the Wright's (1934) procedure.

The steps used by the subjects in solving the problems in the Volumetric Analysis Test were examined for any conceptual errors.

The manual skills of the subjects were identified from the checklist used during the interview. The percentage of subjects using any particular skill in the checklist was computed. This was done for all the interview subjects together as well as for subjects grouped according to the number of titration labs done since Grade 11. Correlation analysis was used to test the relationship between the number of titration labs done and performance on volumetric analysis calculations for all the subjects involved in the study.

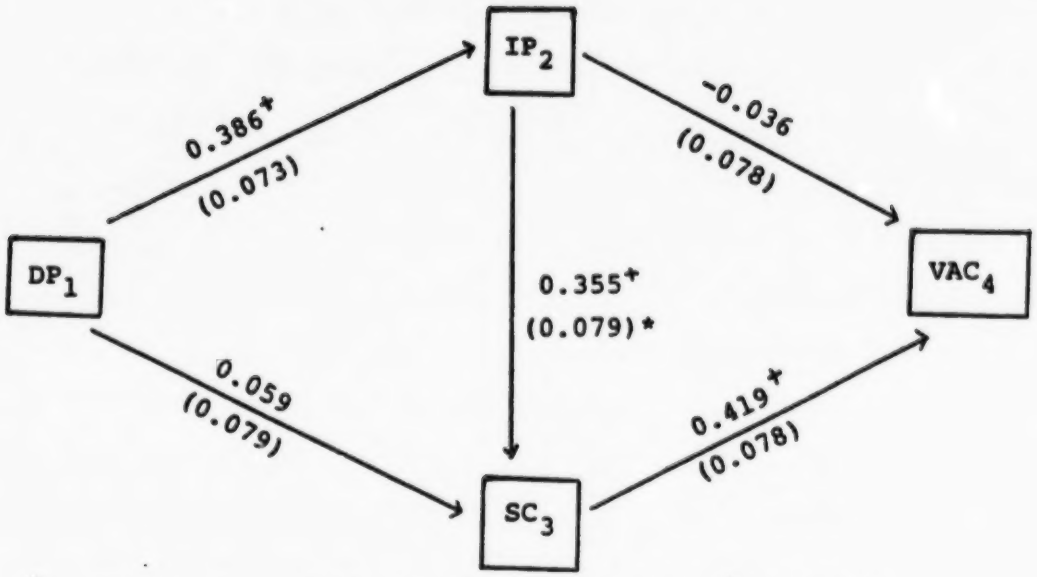
The interview data were analysed using qualitative techniques. The conceptions of the subjects on pH, concentration, indicator behaviour and scientific terminology were analyzed in terms of the response patterns for all the subjects as a group. The data collected from the subjects as they calculated the concentration of the acid from their titration data were used to identify the approaches used by the subjects in their attempt to solve the problem. The analysis was based on whether a formula was explicitly employed or whether proportion was used. The data on the subjects' predictions about the concentration of the acid in the three predictive situations posed in the later part of the interview were analyzed in terms of both the kind of prediction made and the reasons offered. These analyses were conducted in order to obtain a much broader and deeper understanding of the difficulties encountered by the subjects in volumetric analysis.

Results

A. Model Testing

Standardized scores were used in the analyses since preliminary analyses showed that the lack of homogeneity of variance-covariance among the classes observed for the raw scores was due to variance differences.

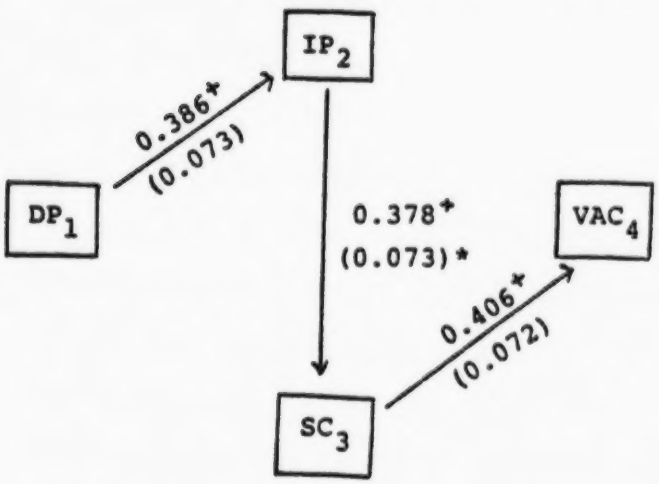
Path analysis of the scores for the subjects using algorithms without understanding (utilizing the subprogram, REGRESSION, in the Statistical Package for the Social Sciences, Nie, et al., 1975) yielded the parameter estimates in Figure 2 for the proposed integrated model. The path coefficients provide an estimate of the direct influence of one variable on the other. The ratio of each path coefficient to its standard error is a t-ratio which provides an indication of the importance of the individual path coefficients. As Figure 2 shows, the path between DP and SC and that between IP and VAC are not essential to the performance of the subjects using algorithms without understanding. Figure 3 presents a trimmed model (Z-model) obtained by deleting the insignificant paths. The chi-square test for both the proposed integrated model and the trimmed model showed that both models provide reasonable explanation of the performance of these subjects. This chi-square test evaluates the goodness-of-fit of the model as a whole. To assist in selecting one of the models, the total associations among the variables in the proposed model were examined. The result of this analysis is provided in Table 1. In the table, spurious effects constitute the part of the total association



* Standard errors in parentheses + P < .05

Note: Model χ^2 = 2.3668 (df = 1), P > .05

Figure 2: Integrated Model for Subjects Using Algorithms Without Understanding (N = 160)



Total Effects

VAC-DP=P_{21} P_{32} P_{43}
= 0.059

VAC-IP=P_{32} P_{43}
= 0.153

SC-DP = P_{21} P_{32}
= 0.146

* Standard errors in parentheses + P < .05

Note: Model χ^2 = 2.0215 (df = 3), P > .05

Figure 3: Trimmed Integrated Model for Subjects Using Algorithms Without Understanding (N = 160)

due to the presence of common causes or correlated causes. The total effect is that part of the total association which is not due to spurious effects; the direct effect is that part of the total effect which is not transmitted via intervening variables, while the indirect effect is that part which is mediated by intervening variables.

The results showed that the indirect effect of DP on SC (0.137) is far greater than its direct effect (0.059). This indirect effect accounts for about 70% of the total effect. A similar situation is found with the direct and indirect influence of IP on VAC.

Analysis of the data for subjects using algorithms with understanding yielded the results in Figure 4. As this figure shows, the path between DP and SC is insignificant in explaining the performance of these subjects. A re-analysis after removal of this path yielded the trimmed model (non Z-model) in Figure 5. The chi-square test for the proposed model and the trimmed model suggested that both models offered a plausible representation of the underlying processes that yielded the data for these subjects. The analysis of the total associations between the variables yielded the values in Table 2. This table shows that the indirect effect of DP on SC through IP accounts for about 60% of the total effect. The negative values in the table indicate that for these subjects direct proportional reasoning may be suppressing the effect of inverse proportional reasoning.

B. Specific Students' difficulties

B.1. Conceptual errors

The conceptual errors identified from the subjects' work on the Volumetric Analysis Test are presented in Table 3. A percentage agreement of 91.5% was obtained when a chemistry graduate student reanalyzed the answer booklets for 12 students.

B.2. Manual Skills

The analysis of the practical skills of the interview subjects showed that the adequacy of their skills varied with the specific skill in question. Thus, whereas most students exhibited satisfactory skills in setting up the experiment, adding an indicator before titration, and shaking the titration flask, an equally large number of them failed to exercise caution when adding the basic solution to the acid or to use a white background to aid in detecting the colour changes of the indicator. This situation was attributable to the different emphases placed on the various manual skills by individual teachers.

A further analysis of the manual skills in terms of the degree of involvement in practical laboratory titrations showed that above a certain degree of involvement (above 5 practical labs) satisfactory manual skills are displayed by the subjects while below this number the skills are not as well developed.

Table 3

Conceptual Errors on the Volumetric Analysis Test*

Error No.	Conceptual Error	Number of Subjects	%
1.	Assumption of 1:1 mole ratio	201	70.0
2.	Concentration of stock solution different from concentration of volume used in titration	99	34.5
3.	Incorrect formula or formula weight	85	29.6
4.	Assumption of 2:1 mole ratios in problems requiring 1:1 mole ratios (especially assuming H_2SO_4 always reacts in a 1:2 ratio)	12	4.2
5.	Reversal of stoichiometric mole ratios	45	15.7
6.	Assume direct proportion between concentration and volume of solutions	37	12.9
7.	Equating concentration with amount (moles) of substance	29	10.1
8.	Calculation of moles of a substance irrespective of its purity	55	19.2
9.	Adding volumes of acid and base together in calculating unknown concentration or vice versa	17	5.9
10.	Difficulties in using mass to calculate concentration or vice versa	45	15.7
11.	Use of balanced chemical equations not considered in problem solution	173	60.3

* Total number of subjects who wrote this test = 287

B.3. Relation of Number of Titration Laboratories to Achievement

The correlation between the number of practical titration labs performed and performance on volumetric analysis calculations was found to be weak ($r = 0.217$, $P < .05$).

B.4. Concepts Involved in an Acid-Base Titration

In analysing the responses of the subjects to the questions asked during the interview, the questions were grouped according to whether they relate to the pH, concentration and mole, indicator behaviour or terminology. Examples of the response patterns are provided in Appendix B. These results have been fully discussed elsewhere (Anamuah-Mensah, 1981).

Concentration and its Relationship to Mole

The interview subjects were found to show adequate understanding of the concepts of concentration and mole. Most of them understood that the concentration will vary with dilution, but will remain invariant when the volume of the solution is decreased. Similarly, almost all of them indicated that the number of moles of a substance in a solution will remain invariant with dilution. However, almost half the subjects indicated that the number of moles will also remain invariant when some of the solution is removed.

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* Anamuah-Mensah, J. Student Difficulties with Volumetric Analysis. Unpublished doctoral dissertation, The University of British Columbia, August, 1981.

pH

The analyses of the students' conceptions about pH indicated that they did not have any difficulties with certain aspects of pH. They could calculate the pH of strong acidic and basic solutions from their concentrations; they knew the pH at the stoichiometric point for the reaction between HCl and NaOH was 7; and they also realized that the pH increased with the addition of a basic solution.

However, difficulties were encountered in other areas:

1. Most students (81%) could not correctly indicate the effect of dilution on the pH of acid solutions,
2. About half of the students could not correctly indicate the differences in the rate of change of pH at the initial stages of titration and near the end, and
3. About half of the subjects held the view that the pH at the stoichiometric point for the titration of a strong acid with a weak base or a strong base with a weak acid will be 7.

Indicator Behaviour

Most of the students were found to show an understanding of the function of indicators in acid-base titrations. However, in selecting indicators for titrations, most students did not relate the pH range of the indicator to the stoichiometric point for the reaction under study. Most of the

explanations offered related to their own laboratory experiences. In the case of the titration of a strong acid with a strong base, the students did not realize that the wide range of pH change at the stoichiometric point allows for the use of a wide variety of indicators.

Most of the students were also found to view indicators as neutral substances whose relative volume does not affect the titration results.

In trying to explain the colour changes which occur in titration only 31.9% of the students referred to the equilibrium between the dissociated and undissociated forms of the indicator.

Terminology

The students showed an inadequate understanding of the terms: endpoint and stoichiometric point even though they used them frequently.

B.5. Approaches to Problem Solution

Table 4 gives a distribution of the interview subjects according to the approach used in calculating the concentration of the acid from the data obtained during the titration and their achievement level on the Volumetric Analysis Test.

Two principal approaches were used by the subjects in calculating the molarity of the acid from the data obtained in the titration. These were the Formula Approach and the Proportional Approach. Two forms of these approaches were

Table 4

Distribution of Interview Sample by Strategy and Achievement Group

N = 47

Strategy	Achievement Group			Total
	High	Medium	Low	
F(B)	10	9	3	22
F(V)	4	4	4	12
P(B)	2	2	2	6
P(V)	0	0	4	4
NC	0	1	2	3
Total	16	16	15	47

$\chi^2 = 14.157$ (df = 8) $.1 < P > .05$ n.s.

identified, namely, the basic and the variant forms. 46.8% of the subjects used the basic form of the Formula Approach while 25.5% used the variant form. Also 12.8% of the subjects used the basic form of the Proportional Approach while 8.5% used the variant form of the Proportional Approach. Thus, over all a large number of the subjects used the Formula Approach in their solutions. It was also found that subjects in the low achievement group used the Proportional Approach to a greater extent than those in the middle and high achievement group. Those using the variant of the Proportional Approach were found to assume direct proportionality between molarity and volume of solution. The analysis of the approaches

also indicated that a large proportion of the subjects did not write balanced equations in their solutions while a substantial number did not indicate the mole ratios in the reaction.

Table 5 gives the distribution of the subjects according to their scores on the three questions which required them to predict the concentration of the acid in three different situations. These situations all involved a 1:2 mole ratio. These situations involved (a) assuming that in the titration, an acid A reacted with a base B in a ratio of 2:1; (b) assuming NaOH reacted with H_2SO_4 in the titration; and (c) assuming HCl reacted with Na_2CO_3 in the titration. The results in Table 5 shows that few students (27.7%) were able to predict correctly in all three situations even though a greater proportion (78.7%) obtained correct solutions to the initial problem which involved a 1:1 mole ratio between HCl and NaOH.

Table 5

Distribution of Subjects According to Approach and number of Correct Responses on the Three Prediction Questions

Approach	3 Correct	2 Correct	1 Correct	None
F(B)	8	4	7	3
F(V)	2	2	4	4
P(B)	3	1	0	2
P(V)	0	1	2	1
NC	0	0	2	1

About 23% failed to make at least one correct prediction. This difficulty was attributed to the fact that some of the subjects assumed 1:1 mole ratios in their predictions while others were unable to coordinate the stoichiometric ratio with other relevant data.

Discussion*

It is seen that for both groups of subjects (i.e. those using 1:1 mole ratios indiscriminately and those using it only where it's required), the proposed integrated model and the trimmed integrated models (i.e. the Z-model and the non Z-model) are all consistent with the kinds of formulations usually made in the science education literature in terms of the explanatory variables (structure and content) used to rationalize students' understanding of school concepts. However, the examination of the relative contributions of the direct and indirect effects suggests that for both groups of subjects, the trimmed models provide a more reasonable explanation of their performance. Also, it has been argued that

> "the potential for refining or trimming a theory, and thus making the theory more parsimonious, clearly is of considerable significance and could be listed along with the issues of explanation ... as a basic gain to be acquired from the construction of linear models." (Heise, 1969, pp. 59-60).

Thus, on the grounds of parsimony and the relative contribution of the indirect effects of the variables, the trimmed models were accepted as being tenable.

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* Detailed discussions of the result can be found elsewhere (Anamuah-Mensah, 1981).

The substantive meaning of the deleted paths in the trimmed integrated model for the subjects using 1:1 stoichiometric ratios indiscriminately is that direct proportional reasoning does not influence knowledge of prerequisite concepts directly and that inverse proportional reasoning does not have a direct influence on performance in volumetric analysis calculations. This seems to be contrary, in some sense, to some of the theoretical analyses performed on some chemical concepts. For example Herron (1975) analyzed some chemical concepts including volumetric analysis calculations and concluded that students will have difficulties in doing volumetric analysis-type calculations because of the inverse proportionality involved. He implied by his analysis that successful performance on such a problem will require the ability to reason using indirect proportion. The empirical result obtained for the trimmed integrated model suggest that indirect proportional reasoning does not have any direct effect on performance in volumetric analysis calculations. Its influence is mainly through the knowledge of the subsumed concepts. Even the result for the proposed integrated model reveals, as already noted above, that the mediating effect of subsumed concepts on volumetric analysis calculations is very substantial. This result is understandable in view of the suggestion in the literature that the content of a task may interact with reasoning ability of the subjects on the task (e.g. Lunzer, 1975).

Ingle and Shayer (1971) also analyzed the mole concept and its associated calculations and concluded that since the mole concept involves proportional (really, direct proportional) reasoning, high school students who can't reason in this way will find it difficult to comprehend these concepts. This analysis implies a direct effect of direct proportional reasoning. The above empirical result for the trimmed integrated model indicates, however, that direct proportional reasoning does not have any direct effect on the prerequisite concepts (which includes the mole concept). It treats its effect on subsumed concepts solely as being transmitted via inverse proportional reasoning. This latter result is also evidenced in the trimmed integrated model for the subjects using 1:1 mole ratios with understanding.

It could be that, since direct proportional reasoning precedes and is subsumed by inverse proportional reasoning, even though both forms of reasoning may measure the same 'intellective' ability (Lovell and Butterworth, 1966), most of the effect of direct proportional reasoning is transmitted through inverse proportional reasoning as soon as this latter reasoning ability is developed. Also, it seems reasonable to hypothesize that with tasks involving solely direct proportions or simple ratios, the unmediated influence of direct proportional reasoning may be considerable (i.e. direct proportional reasoning will be displayed in the solution to the task). But where formulas or algorithms could be applied this direct effect may become small. Similarly, the direct influence of

inverse proportional reasoning may become important in tasks requiring its use. However, where there is a formula which could be applied as in the case of volumetric analysis calculations, this direct effect may diminish while its effect through the application of the formula may become substantial.

Also the above results for the two groups of subjects identified in the study indicate that in both the original model and the trimmed models, direct proportional reasoning has a direct influence on inverse proportional reasoning. This is consistent with the results obtained by others (Rogers, 1977). It also suggests that direct proportional reasoning precedes inverse proportional reasoning in acquisition. It suggests further that inverse proportional reasoning influences knowledge of subsumed prerequisite concepts which in turn affects performance on volumetric analysis calculations. The significant effect of subsumed prerequisite concepts compared with inverse proportional reasoning on performance in volumetric analysis calculations, is not unexpected since in the studies by Wheeler and Kass (1977) and Griffiths (1979) subsumed concepts (or content) were found to be more important than the reasoning ability of the subjects.

The results for the subjects who tend to use incorrect stoichiometric ratios in their calculations seem to suggest (as explained above) that with these subjects the ability to reason using direct proportion may be hiding the true effect of their inverse proportional reasoning ability in volumetric analysis calculations. It could be argued that since some of

these subjects (as borne out by the interview data discussed later) assumed a direct proportional relation instead of an inverse one between molarity and volume even though they can reason using inverse proportion, this ability to reason using inverse proportion tends to have a slight negative influence on their performance on volumetric analysis calculations. It is suggested that this behaviour of the subjects may reflect on the structural complexity of volumetric analysis problems -- that is, the fact that it involves both direct and inverse relationships. As such, the students probably become confused over which relation is applicable between which two variables. It could be that these subjects who have already acquired direct proportional reasoning are in the 'transitional stage' in their development of inverse proportional reasoning. As such, since the latter is not well formed, they tend to use direct proportional reasoning to a greater extent.

Again, it is suggested here that the strong influence of prerequisite concepts on volumetric analysis calculations for these subjects may mean that the mediating influence of prerequisite concepts may be essential to their performance on the calculations since they tend to get confused over which structural relation they have to use. It could be that some of these subjects employ formulas in their solutions with an understanding of the basic concepts involved thereby increasing the influence of the subconcepts on performance on volumetric analysis calculations.

The significance of the direct effect of inverse proportional reasoning on volumetric analysis calculations for subjects who use algorithms with understanding, suggests that for these subjects both the prerequisite concepts and the ability to reason using inverse proportion are important. The moderate values may however reflect on the difficulty encountered by some of them when using the stoichiometric coefficients in calculations (see Table 3).

Most of the errors made by the subjects (Table 3) relate to the misunderstanding of the basic content (e.g. ability to write correct formulas and equations, ability to identify when a particular learned algorithm is appropriate) in the area while a few (e.g. reversal of mole ratio) were related to the logical structure of the problems. Some of the conceptual errors (e.g. the indiscriminate use of 1:1 mole ratio) were also noted by Duncan and Johnstone (1973) and Rowell and Dawson (1980).

On the concepts (concentration and mole, pH, indicator behaviour, endpoint and stoichiometric point) involved in titration, the result of the students' responses seemed to indicate that most students encounter difficulties with mole, pH, indicator behaviour and terminology. This is despite the fact that these concepts have been taught by the teachers.

In general,it seems an adequate understanding of these concepts as they are reflected in the questions posed in this study, will require an understanding of:

1) the effect of water on the pH of solutions
2) the pH at the stoichiometric point for different acid-base reactions
   a) the nature of the acid and base, i.e. whether strong or weak and what makes them so,
   b) the hydrolysis of their salt.
3) the mechanisms of indicator behaviour (colour changes)
4) the effect of increased concentration of indicator on volume of base used in titration
5) choice of indicators for acid-base reactions
   a) the relationship between the pH at the stoichiometric point and the pH range of the indicator
   b) the nature of indicators
   c) the changes in pH during titration (i.e. a clear understanding of titration curves)
6) the correct use of the scientific terms - stoichiometric point and endpoint.

The low correlation between prior number of titrations and performance on volumetric analysis suggests that involvement in laboratory experiments may not strongly influence the achievement of students on cognitive tasks. This may relate to the objectives that the individual teachers have for practical work.

It seems that in titration experiments in the schools, much more emphasis is placed on the student being able to obtain the volumes for subsequent use in their calculations. Also it seems some emphasis is placed on the

manipulation techniques required to obtain accurate volumes. However, no attempt is made to see whether the subject understand the processes occurring in the experiment. Neither is sufficient attention given to how the students relate the various concepts they have learned in different lessons such as concentration, moles, pH and hydrolysis during the titration. If one of the objectives of practical work is to help students to obtain better understanding of the theory, it seems this could be achieved if attempts are made to question the students on the processes and their observations as they are doing experiments.

The above difficulties faced by students on volumetric analysis may partly be ascribed to the fact that chemistry, in contrast to physics and biology, is two steps removed from everyday life. That is, before a subject can draw any meaningful conclusions from say, a chemical experiment, the subject's observation (e.g. the acid solution is colourless with the addition of the indicator) has to be translated into a mental picture (e.g. the indicator contain charged ions in equilibrium with the molecular form, and these are moving among the ions of acid and water molecules) or chemical formulas. It has been argued (Gunning and Johnstone, 1976) that teachers take this two-step process, which is particularly applicable to chemistry, for granted.

Delimitations of the Study

The topic chosen for the study, namely, volumetric analysis is a broad one involving several concepts, laboratory skills, volumetric analysis calculations and the mechanical process of titration. Other subsidiary components are the role of indicators in titration, use of oxidation-reduction reactants, the pH of acidic and basic solutions, the construction and interpretation of titration curves, and back titrations.

The restriction of this study to some selected aspects of volumetric analysis (titration calculations laboratory skills, role of indicators and pH) without considering oxidation - reduction reactions as well as titration curves per se is recognized as a delimitation of the study. The restriction of the prerequisite concepts to a selected set of subsumed prerequisite concepts also represents an important delimitation of the study. However, other researchers (Gower, Daniels and Lloyd, 1977a; Toon and Ellis, 1973) have proposed similar prerequisite concepts for volumetric analysis calculations. In any case, note is taken of the possibility that different researchers may hypothesize other subsumed concepts in addition to the ones used in the study. Also cognisance is taken of the possibility that other researchers may wish to stress other aspects of volumetric analysis instead of the ones chosen for this study.

A further delimitation is the use of students in only one grade level (Grade 12) in one Canadian City (Vancouver). It is noted that even in the same school,

students with different motivations or interests may respond differently (Lovell, 1971) to the tests. Volunteer subjects were used and the optional nature of the course puts the subjects in a self-selective group. Thus, while any results from the study may be suggestive, one has to be cautious in generalizing to other situations. However, one consolation is that in British Columbia Schools the unit on acids and bases which includes volumetric analysis is taught only in the Grade 12 chemistry course even though in Grade 11 students perform one practical experiment on titrations.

Implications

Although the study is exploratory, a number of implications can be inferred from the interpretation of the results. The finding that the performance of subjects using 1:1 mole ratios indiscriminately and those using 1:1 mole ratios discriminately are explained by two different trimmed integrated models seems to suggest that these groups of students may have different cognitive strategies and also that they may differ in other important ways. It also points to the appropriateness of grouping chemistry students on the basis of their comprehension of the mole ratios in a balanced chemical reaction. If chemistry teachers are aware of this difference they may be in a better position to help improve the strategies used by those students who apply the 1:1 mole ratios indiscriminately in their calculations. The finding that for both groups of subjects, subsumed concepts and

proportional reasoning had important effects, points to the probable usefulness in combining the Gagnean and Piagetian theories into a single model which could be used to explain a subject's difficulties with chemical problems. For the subjects using algorithms without understanding, the finding that the direct effects of subsumed concepts on volumetric analysis calculations is negligible supports the notion expressed by others (e.g. Wheeler and Kass, 1977) that the content of a task may be more important than the structure. However, the considerable indirect influence of inverse proportional reasoning on volumetric analysis calculations through subsumed concepts implies that inverse proportional reasoning may interact with subsumed concepts. It also suggests that the theoretical assertion that inverse proportional reasoning may have a direct influence on performance on chemical problems may not be completely justified. For the subjects using stoichiometric ratios with understanding, the significance of the direct influence of inverse proportional reasoning on volumetric analysis calculations indicates that these subjects probably identify and apply the correct relationship between molarity and volume of solution.

The negligible direct effect of direct proportional reasoning on knowledge of subsumed concepts for both groups suggests that since both direct and inverse proportional reasoning measure the same intellective ability (Lovell and Butterworth, 1966) and that inverse proportional reasoning is a later development (e.g. Rogers, 1977), the effect of direct proportional reasoning on subsumed concepts may be channelled through

inverse proportional reasoning as soon as this later ability is developed.

The interview results and the results of the conceptual errors point to the need for teachers to be aware of the assumptions which students may have in a given teaching situation so as to adopt teaching strategies which will minimize such misconceptions. The poor understanding of the concepts (pH, indicator behaviour and concentration) as they are manifested in titrations suggests a move away from the highly prescriptive "cook-book" laboratory which occurs in most schools to a less prescriptive type. The adoption of the less prescriptive type may help students to understand the possible implications and explanations of their actions and observations during practical work. This type of practical work may require the students to make decisions on their own in the selection of equipment and solutions for practical work. It is to be hoped that these decisions would tend to be based on a sound chemical knowledge rather than on the students' familiarity with the equipment or solutions. The chemistry teacher can facilitate this process through asking questions (such as those used in the interview) which can identify the students' reasoning at various stages in the investigation. As some of the students reported that they have "never been asked these kinds of questions", it seems that an emphasis on the students' understanding of the processes occuring during an investigation may go a long way to improve their general understanding of chemical concepts. It will also help the students to integrate

in a meaningful way, the various concepts which they have learned in isolation in different lessons.

In order to provide ample time for chemistry teachers to effect this less prescriptive approach, it seems that chemistry instruction in the secondary school may have to move away from the encyclopedic coverage of the concepts to teaching fewer concepts for greater conceptual understanding.

The onus may also be placed on curriculum writers. They also have to move away from the usual practice of providing "cook-book" type experiments in laboratory texts written for students.

Also, the poor understanding shown on the concepts entailed in a titration and the inadequate manual skills displayed by the subjects points to the need for teachers to examine the objectives that they may have for practical work and whether these are communicated well to the students.

The finding that the students use mainly two approaches (proportional and formula approaches) to solve volumetric analysis problems may have important educational implications. It may tell teachers that as well as a particular approach fostered by them, the students may employ other approaches. With this knowledge, instead of stressing only one particular approach in their teaching, the teachers can emphasize possible alternate routes to the solution of the problems so that students whose learning styles or processing abilities make them comfortable with the alternative routes may also gain insight into the problem.

Also, the finding that a high percentage of those using the Formula Approach obtained correct answers to the problems, may suggest that teachers may have to encourage more students to use this approach. However, they have to be aware that blind emphasis on the use of formulas without considering whether the students understand the relationships among the variables entailed by the formulas may lead the student nowhere and hence must be guarded against.

Future Research

The results and implications of the study suggest the following areas for future research:

1. In order to identify the stability of the trimmed integrated model as a plausible explanatory system for subjects' performance on chemical concepts, the need exists for a replication of this study in other geographical areas and with other chemical concepts. In such a study, it may be necessary to gather further qualitative data on the relationship between direct proportional reasoning and the subjects' understanding of the subsumed prerequisite concepts so as to allow a full interpretation of the model. This model testing could be done for chemistry subjects grouped according to their use of the stoichiometric ratio in calculations.
2. The use of qualitative data to explain some of the quantitative results points to the need for further investigation of the role of qualitative information as a supplement to quantitative data.

3. Since the students were found to exhibit different levels of skills in their titration and also showed some misunderstanding of some of the concepts entailed by a titration, it seems necessary to examine the objectives that teachers have for practical work. Such a study could be conducted by using a questionnaire as was done in the United Kingdom by Kerr (1963) and Thompson (1975). The questionnaire could be used in conjunction with the observation of actual practical work in the schools. Hopefully, this would reveal any differences in the emphases given to different objectives. It would also reveal whether developing an understanding of the processes occuring during laboratory investigation is considered important. Also, the results of such a study would provide curriculum developers and revisors with a base for action.

Also, the misunderstandings displayed by the interview subjects on pH, indicator behaviour etc., during the titration, points to the need for further studies aimed at examining the kinds of understanding that groups of students have when performing laboratory experiments. In doing this, it may be necessary to consider other variables such as the students' interest in chemistry and their future aspirations. These additional variables may tell us why certain subjects perform the way they do.

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APPENDIX A

EXAMPLES OF ITEMS USED IN THE TESTS

Classroom Proportionality Test

General Directions:

For each of the items below a situation will be demonstrated. Each demonstration will lead to a question for which there are a number of possible answers. For each item you are to check the box of the best answer and explain your choice in the space provided.

Direct Proportionality Subtest

Item 1: "Plastic Cylinders 1"

Materials:

1 wide plastic cylinder (3.8 cm in diameter)

1 narrow plastic cylinder (2.5 cm in diameter)

1 jar of coloured water

Specific Directions:

Show the students the two plastic cylinders. Point out the different diameters and the equally spaced marks along the front of each. Pour water from the jar into the wide cylinder up to the 4th mark. Pour that water into the narrow cylinder and note that the water rises to the 6th mark. Tell the students to make a record of this information. Pour the water from the narrow cylinder into the jar. Pour water from the jar into the wide cylinder up to the 6th mark.

Ask:

How high would this water rise if it were poured into the narrow cylinder?

Item 1: "Plastic Cylinders 1"

The water will rise to mark:

[ ] 7

[ ] 8

[ ] 9

[ ] 10

[ ] There is no way of predicting

Please explain your choice

Item 2: "Plastic Cylinders 2"

Materials:

Same as for Item 1.

Directions:

Start with empty cylinders. Pour water from the jar up to the 11th mark in the narrow cylinder.

Ask:

How high would this water rise if it were poured into the wide cylinder.

Items 2: "Plastic Cylinders 2"

The water will rise to mark:

[ ] 5-1/3

[ ] 5-2/3

[ ] 7-1/3

[ ] 8-1/3

[ ] 9

Please explain your choice

Inverse Proportionality Subtest

Item 1: "The Balance Beam 1"

Materials:

1 balance beam

a 10-unit hanging weight

a 5-unit hanging weight

Directions:

Show the students the balance beam and the two hanging weights. Hang the 10-unit weight 7 mark out from the fulcrum on one side of the beam. Point out that the 10-unit weight is hanging at 7 marks from the centre.

Ask:

Where would you hang the 5-unit weight to make the beam balance.

[ ] between 3 and 4

[ ] mark 7

[ ] mark 12

[ ] mark 14

[ ] at the end

Please explain your choice

Item 2: "The Balancing Beam 2"

Materials:

1 balance beam

a 9-unit hanging weight

a 12-unit hanging weight

Directions:

Show the students the balance beam and the two hanging weights. Hang the 12-unit weight 6 marks out from the fulcrum on one side of the beam. Point out that the 12-unit weight is hanging at 6 marks from the centre.

Ask:

Where would you hang the 9-unit weight to make the beam balance?

[ ] mark 3

[ ] between mark 4 and mark 5

[ ] mark 8

[ ] mark 9

[ ] mark 18

Please explain your choice

Subconcepts Test

Item 1: Which of the following HCl solutions is most concentrated?

A 500 ml of 2M HCl

B 1000 ml of 3M HCl

C 300 ml of 4M HCl

D 800 ml of 5M HCl

E 500 ml of 6M HCl

Item 2: What volume of 5M NaOH is needed to prepare 200 ml of 2M NaOH solution?

A 15 ml

B 20 ml

C 40 ml

D 80 ml

E None of the above

Item 3: Given this equation: $2SO_2 + O_2 \text{ — } 2SO_3$

What mass of SO_2 would react with 32g of O_2?

A 32g

B 64g

C 96g

D 128g

E 130g

Item 4: The number of moles of NaCl in a two pound (908g) box of table salt is:

A 0.0644 mol

B 15.5 mol

C 58.5 mol

D 72.0 mol

E 5.31×10^4 mol

Item 5: Calculate the mass of ammonia (NH_3) containing twice as many molecules as 32 grams of oxygen (O_2).

A 17g

B 32g

C 34g

D 6.02×10^{23}g

E None of the above

Item 6: Which of the following is NOT involved in balancing chemical equations?

A conservation of atoms

B conservation of mass

C conservation of energy

D conservation of molecules

E conservation of electrons

Item 7: Consider the following equation:

$2Al + Fe_2O_3 \text{ — } 2Fe + Al_2O_3$

The TRUE statement about the equation is:

A 2g Al will react with 1g of Fe_2O_3

B 2 moles Al will produce 2 moles of Fe

C 1g of Fe_2O_3 will produce 2 moles of Fe

D 1 mole of Fe_2O_3 will produce 1g Al_2O_3

E 2g Al produce 2g of Fe

Volumetric Analysis Test

Directions:

This is a test of how you arrive at solutions to certain chemical problems. It is therefore very important that you show all your work in the sapces provided. We are very much interested in the steps you use to arrive at a solution.

Item 1: How many milliliters of 0.20 M NaOH are required to neutralize 50.0 ml of 0.10 M HCl?

Item 2: A 500 ml solution of HCl is prepared for use in a class experiment. If 40.0 ml of this neutralizes 25.0 ml of 1.0 M Na_2CO_3 solution what is the concentration of the original solution of HCl?

Item 3: If 25.0 ml of 0.5 M Na_2CO_3 solution neutralizes 25.0 ml of HCl, what is the concentration of HCl?

APPENDIX B

Questions and Response Patterns Derived From Interview Data in the Area of pH

Response Pattern	Number of Students	%
Question 1: The sodium hydroxide solution you are using in the titration is 0.1M, what will be its pH?		
1. The pH will be 13 since pH = -log $[H^+]$ and pH = 14-POH	32	68.1
2. I don't know	5	10.6
3. The pH will be 1	3	6.4
4. The pH will be 13 since antilog of dissociation constant gives POH	1	2.1
5. pH will be 0.1 because concentration is 0.1	1	2.1
6. Others[a]	5	10.6
Question 2: If the hydrochloric acid you are using is 0.1M, what will be its pH?		
1. pH is negative logarithm of the hydrogen ion concentration so it will be 1	35	74.5
2. I don't know	6	12.8
3. pH of 1 is the highest for an acid so it will be 1	1	2.1
4. pH will be antilog of dissociation constant which is 1	1	2.1
5. pH will be 0.1	2	4.3
6. Other[a]	2	4.3

[a] This response pattern represents students answers which were either non-interpretable or very unusual.

Response Pattern	Number of Students	%
Question 5: As you're adding sodium hydroxide solution to the acid in the flask, what do you think happens to the pH of the solution in the flask?		
1. The pH will increase toward pH of 7	40	85.1
2. The pH will decrease	5	10.6
3. It will stay the same	2	4.3
Question 6: How does the pH change at the initial stages of the titration compare to the change near the stoichiometric point for a given volume of added base?		
1. The titration curve shows that it changes slowly at the beginning but shoots up near the stoichiometric point	7	14.9
2. It will be greater near the stoichiometric point because there will be smaller amount of H^+ ions remaining near the stoichiometric point.	16	34.0
3. It will be slower near the stoichiometric point because the moles of hydrogen ions will be less compared to the initial stages.	6	12.8
4. The pH change will be the same because a drop is a drop, it changes the same way.[d]	14	29.8
5. The pH will level off near the stoichiometric point	1	2.1
6. I don't know	3	6.4
Question 7: What will be the pH at the point when there are equal amounts of acid and base?		
1. The pH will be 7	42	89.4
2. The pH will be less than 7	5	10.6

[d] One person gave this response but did not know why.

[c] Of the 5 students who indicated that the pH will decrease with the addition of base, 2 gave response (2), 1 gave response (3), 1 gave response (5) and 1 gave response (6).

	Response Pattern	Number of Students	%
Question 8: When you overrun the endpoint of the titration, what will the pH be?			
1.	The pH will be more than 7	37	78.7
2.	The pH will be lower than 7	4	8.5
3.	The pH remains at 7	3	6.4
4.	Others[e]	3	6.4
Question 12: If you use acetic acid instead of HCl in the titration against NaOH, what will be the pH at the stoichiometric point?			
1.	It will be greater than pH 7 because acetic acid is a weak acid	14	29.8
2.	The pH will be 7 since 7 is the neutral point when they have reacted completely	23	48.9
3.	The pH will be 7 since NaOH is strong	1	2.1
4.	The pH will be less than 7 since acetic acid is a weak acid	2	4.3
5.	The pH will be below 7 because of the ratio of concentration of base to acid and the K_b value	1	2.1
6.	pH will be zero because water has pH of zero	1	2.1
7.	The pH will be 4 since 4 is the stoichiometric point for NaOH + HCl	1	2.1
8.	The pH will be below 7 because acetic is a strong acid	1	2.1
9.	pH will be 1 because pH does not depend on the nature of the acid	1	2.1
10.	I don't know	2	2.1

[e] For example
a) pH will remain at 1
b) pH will be 13 since it's just addition of base to H_2O
c) pH will remain at 0

Questions and Response Patterns Derived from Interview Data in the Area of Concentration

Response Pattern	Number of Students	%
Question 3: You took 25 mL of hydrochloric acid from the stock solution in the bottle. Do you think the 25 mL taken out from the stock solution will have any effect on the concentration of the remaining stock solution? Why?		
1. The concentration will be the same because concentration is the same throughout the entire solution	31	66.0
2. It will stay the same because you're not adding or taking anything	3	6.4
3. I don't think it will change because I'm taking equal proportion of acid and water	12	25.5
4. I don't know	1	2.1
Question 4: Will the volume taken from the stock solution affect the number of moles of acid in the remaining stock solution? Why?		
1. It will be less because you're taking something (moles or volume) out of the stock solution	26	55.3
2. The concentration is the same, the volume changes so the number of moles will decrease	6	12.8
3. The number of moles stays the same[b]	15	31.9
Question 9: During the titration you used distilled water to flush down the acid on the sides of the flask, what effect will this water have on the concentration of the solution in the flask?		
1. It will decrease the concentration since the volume will be greater	26	55.3

[b] Reasons given are explained in the text

Questions and Response Patterns Derived from Interview Data in the Area of Indicator Behaviour

Response Pattern	Number of Students	%
Question 14: Why is an indicator needed in this titration?		
1. To indicate when the moles of base equals moles of acid	24	51.1
2. To indicate when the solution is neutral	12	25.5
3. To indicate when the solution has reached a certain pH range	7	14.9
4. To show when the solution is basic	3	6.4
5. I don't know	1	2.1
Question 15: You noted that the indicator had different colours in different mediums, how does the indicator change colour?		
1. The indicator is a weak acid or base with two differently coloured forms in equilibrium. The proportion of these forms in solution determines the colour of the solution	15	31.9
2. The indicator reacts with the H^+ or OH^- ions to form coloured compounds	7	14.9
3. It's something to do with electrons in solution	2	4.3
4. I can't explain	21	44.7
5. Other	2	4.3
Question 16: Do you think the amount of indicator added will affect the final volume of base used in the titration? Why?		
1. Yes, the indicator will react with the base to affect the volume of the base	10	21.3
2. It will affect the volume of base because the indicator will increase the pH of the acid	2	4.3
3. It will affect it but I don't know why	1	2.1

Response Pattern	Number of Students	%
Question 16 continued ...		
4. I don't think so because it only makes the colour more perceptible	11	23.4
5. No because an indicator is only there to show the endpoint	17	36.1
6. I don't think so because the indicator is a weak acid	3	6.4
7. I don't know	3	6.4

Question 17: Why did you choose this (particular) indicator for the titration?

Indicator Chosen	Response Pattern	Number of Students	%
Bromthymol blue	1. Because it changes between pH 6 to pH 7.6 which covers the neutral pH range	8	17.0
	2. Because it changes between pH 6-7.6 which covers pH 7 of the base	1	2.1
	3. Because it gives a distinct colour	2	4.3
	4. Because I'm familiar with it	2	4.3
Phenolph-thalein	1. Because pH range falls on vertical section of the graph	2	4.3
	2. Because it changes in the basic range	3	6.4
	3. Because it gives a distinct colour	4	8.5
	4. Because the acid is in the titrating flask	2	4.3
	5. Because I'm familiar with it	16	34.1
	6. I don't know	2	4.3

Indicator Chosen	Response Pattern	Number of Students	%
Question 17 continued ...			
Phenolph-thalein	7. Because the reaction is completed between pH 8 and 10	1	2.1
	8. Because phenolphythalein is in the neutral pH range	1	2.1
Methyl orange	1. Because the acid is in the flask	1	2.1
	2. Because it gives a distinct colour	1	2.1
All three indicators	1. To make sure that at least one of them indicates the endpoint	1	2.1
Question 18: If acetic acid is used in the titration instead of HCl which of the 3 indicators (bromothymol blue, phenolphthalein and methyl orange) will you use in the titration? Why?			
Bromthymol blue	1. Because pH of final solution will be around 7	7	14.9
	2. Because the stoichiometric point will be around pH 6	1	2.1
	3. Because I'm familiar with it	1	2.1
	4. I don't know	1	2.1
Phenolph-thalein	1. Because it changes in the basic range	1	2.1
	2. Because it's pH range coincides with the stoichiometric point	14	29.8
	3. Because pH at equivalence point is 7	3	6.4
	4. Because it is a weaker acid than acetic acid	1	2.1
	5. Because it is used when acid is in the flask	2	4.3
	6. Because I'm familiar with it	7	14.9
	7. I don't know	1	2.1

Indicator Chosen	Response Pattern	Number of Students	%
Question 18 continued ...			
Methyl orange	1. Because acetic acid is a weak acid	2	4.3
	2. Because it is used when the acid is in the flask	1	2.1
	3. I don't know	1	2.1
None	1. I don't know	3	6.4
Others	1. I'll use both methyl orange and bromthymol blue (no reason)	1	2.1

Question 19: If ammonia is used in the titration which indicator out of the three will you choose?

1. Bromothymol blue	9	19.1
2. Phenolphthalein	21	44.7
3. Methyl orange	13	27.7
4. I don't know	4	8.5

Question 20: Do you think you could have used any of the other indicators in this titration? Why?

Indicator not used in Titration	Response Pattern	Number of Students	%
Methyl orange	1. Could be used because pH range will fall on vertical section of graph	2	4.4
	2. Could be used because HCl is stronger acid than methyl orange	1	2.2
	3. Could be used because it's an indicator	4	8.9

Indicator not used in Titration	Response Pattern	Number of Students	%
Question 20 continued ...			
Methyl orange	4. Could be used because choice of indicator depends on whether you're finding the concentration of the acid or base in the flask	3	6.7
	5. No because pH of methyl orange is far too low	27	60.0
	6. No because pH of methyl orange doesn't span the acid and basic range	1	2.2
	7. No, I'm not familiar with methyl orange	5	11.1
	8. No, but I don't know why	1	2.2
	9. I don't know	1	2.2
Phenolph-thalein	1. I can't use it because it's pH does not span the acidic and basic range	1	6.7
	2. I can't because the colour is not distinct	1	6.7
	3. Can't because pH is high	7	46.7
	4. Could be used because its range will fall on vertical section of graph	1	6.7
	5. Could be used because choice of indicator depends on whether acid or base is in the flask	1	6.7
	6. Could use it because pH is close enough to 7	2	13.3
	7. I don't know	2	13.3
Bromthymol blue	1. Could be used because its pH range will fall on vertical section of graph	3	9.1

Indicator not used in Titration	Response Pattern	Number of Students	%
Question 20 continued ...			
Bromothymol blue	2. Could have used it because pH goes over 7	4	12.1
	3. Could have used it because it's an indicator	4	12.1
	4. Could have used it since choice of indicator depends on whether acid or base in the flask	2	6.1
	5. Could be used because HCl is stronger than bromothymol blue	1	3.0
	6. Could have used it because pH range is around stoichiometric point	5	15.2
	7. No, because I'm not familiar with it	3	9.1
	8. Can't because pH range is low	9	27.3
	9. Can't because pH is near neutral range	1	3.0
	10. I don't know	1	3.0